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Resonant Excitation of High Gradient Plasma Wakefield Acceleration By a Train of Micron Sized Pulses

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1. Physics Background

It is well known that recently there are rapid progresses in the field of laser driven wakefield acceleration, particularly in the area of self-modulated laser wakefield accelerations. If one takes a close look at the scheme, a conclusion can be made that wakefield is generated by a train of short but intense laser pulses (this laser pulse train is obtained via non-linear laser --plasma interaction). Or we can simply call it multiple laser pulses driven wakefield acceleration scheme. The idea is all the laser pulses act coherently and thus produce high gradient behind. Although this is impossible to create a train of small laser pulses separated only by a tens of micron meters, but through injection of an intense laser beam into a high density plasmas, through a complicated plasma - laser interaction, the laser beam will be self modulated by Raman scattering process (non-linear), therefore generate a train of little pulses for high gradient wakefield accelerations. To date, the highest gradient achieved is around 100 GV/m. However, there are some disadvantages associated with this scheme (my view). I am listing them as below:

1. Limited acceleration distance due to the laser diffraction, several Rayleigh lengths are the maximum. There are a lot of efforts to extend the acceleration distances, such as waveguiding and channelings. This issue could be overcome by technology advances.
2. Limited acceleration distance due to the dephasing (laser does not travel at the speed of light in plasmas, but electron does).

One can also make a similar approach if one uses electron beam as a driver for the plasma wakefield acceleration. To date, all the electron driven schemes are concentrated on a single short electron beam to drive wakefield in plasma with plasma wavelength comparable to the electron pulse length. This has set an upper limit to all the wakefield gradient limited the electron beam technologies. In the past, we have considered using a multiple laser pulse to drive an RF photocathode gun and presented the idea in the recent AAC meetings. So far, the best experiment results obtained is 20 - 30 MV/m at the Argonne Wakefield Accelerator by a group from UCLA.

2. Wakefield generated in plasma by a single and a train of electron pulses (Only linear plasma theory applied here)

Assume an electron pulse with charge Q and pulse lengthσ_z passing through a plasma cell with density n_0, it will leave a wakefield behind as (approximation)

$$E_z = \frac{n_b}{n_0} 96\sqrt{n_0}\, e^{-(k_p \sigma_z)^2/2} \cos(k_p z)$$

where n_b is electron density

$$n_b = \frac{6 \cdot 10^9 Q}{2\sigma_z \beta \varepsilon}$$

and β is beta function of the electron beam andε is transverse rms emittance.

If one uses a multiple electron pulses from an FEL with spacing ofλp (reason is given in next section), then the wakefield can be expressed as (simple superposition)

$$E_z = \frac{n_b}{n_0} 96\sqrt{n_0} \sum_{i=1}^{m} \int_{-\infty}^{z} \frac{1}{\sigma_z (2\pi)^{1/2}} e^{-(z_0 - i\lambda_{pp})^2/2\sigma_z^2} \cos[k_p (z_0 - z)]$$

Although above expression is for gaussian beam distributions, it can also be used for ANY distribution by simple subsititions.

3. Sources of an electron pulse train and plasma generation

Recently, through discussions with J. Donohue and Z. Huang, I realized that a bunched electron beam from an FEL machine is almost a perfect source for the wakefield experiment. The physics aspect of the bunching is ignored here (an FEL expert can explain this much better). We will perform some simple wakefield acceleration to demonstrate the idea.

Schematic diagram of the scheme is shown in Figure 1, a low energy but high quality electron beam from an RF injector is transported through an undulator magnet. If beam condition matches the bunching conditions, the electron beam will self bunch. After the undulator exit, this bunched electron beam is then accelerated to much higher energy while still maintain a good bunching property (this will be a difficult technological challenge). At much higher energy, this drive beam can be used for WF acceleration now. Another important feature of this scheme is witness beam generation, one can generate a small amount charge just follows the drive beam (a few ps later). Since this small witness beam is hard to bunch itself in the undulator channel, one may has to inject a laser beam (such as CO_2), and this beam will bunch according to IFEL process (BNL ATF has done a lot of this type of works). So this witness can be synchronized with the drive beam

Advantages of this scheme from experimental point of view are one can use the FEL beam from the undulator to ionize the gas to form a plasma channel, then injected electron beam for wakefield excitations.

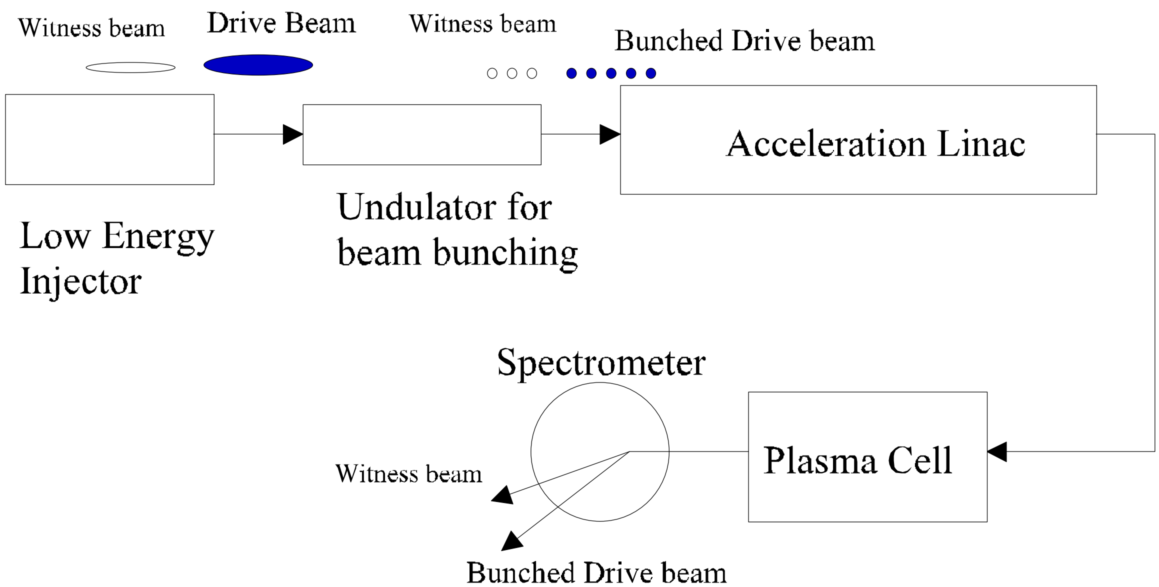

Figure 1. Schematic Diagram of this proposed WF set-up. A low energy electron injector is used here to generate a drive beam and a witness beam. Undulator is to be used for beam bunching and the acceleration linac will boost both beam energies so not only high gradient can be achieved in plasma WF, but also relative long distance of accelerations.

4. Numerical Calculations

I have written a Mathcad program to calculate the above equation. I give results here taken from a set of input parameters:

Total pulses in the bunched beam Q=300 pc (total), Q = 0.03 nC (m=10), 1 GeV with emittance 1 mm -mrad and beta function of 100 cm. This gives beam density $1.8*10^{16}$ /cm^3. The bunch shape used in this simulation is $sin^2(x)$ instead a gaussian (as shown in the next figure dashed line).. If we use 50 micron FEL, then the wakefield can be obtained as high as 10 GV/m.

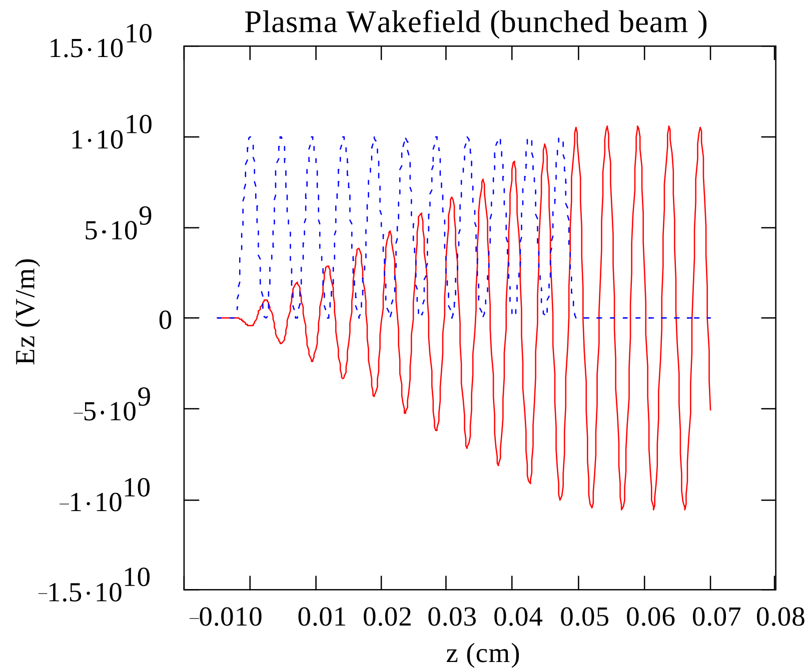

Figure 2. Wakefield generated by a train of FEL bunched beam with good bunching properties. The peak wakefield can be as high as 15 GV/m. The wavelength of both FEL and WF excitation is 50 µm. Total drive beam charge is 300 pc.

If beam is not well bunched as shown in the next Figure 3 (only half good as in Figure 2), then the wakefield is 5 GV/m, still very high gradient.

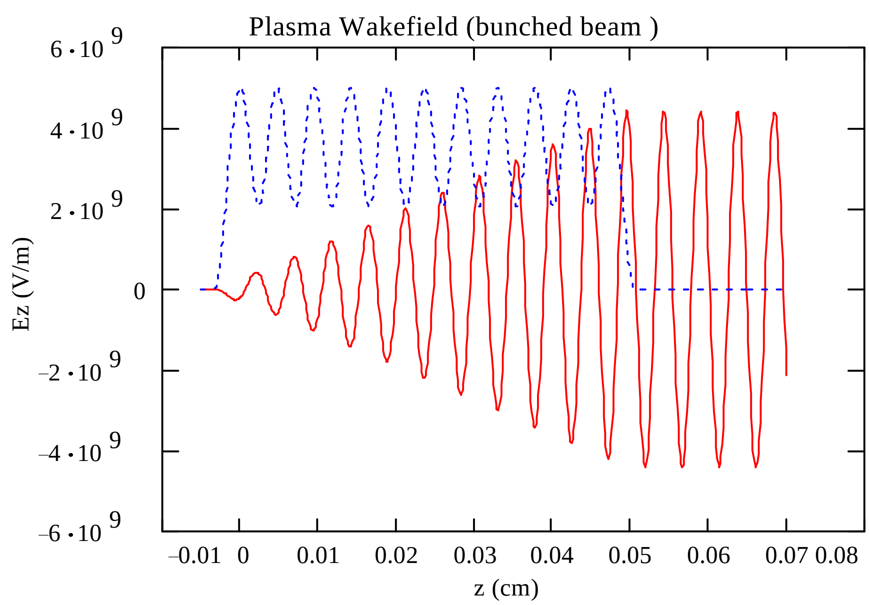

Figure 3: WF generated by the same electron beam as in figure, except the electron beam are not well bunched (more close to realistic case). However, it still gives high WF gradient in comparison with unbunched beam.

For comparison, Figure below gives the wakefield plot for a single unbunched electron beam, in a plasma density of 10^{15}. The Wakefield amplitude is only about 20 - 30 MV/m.

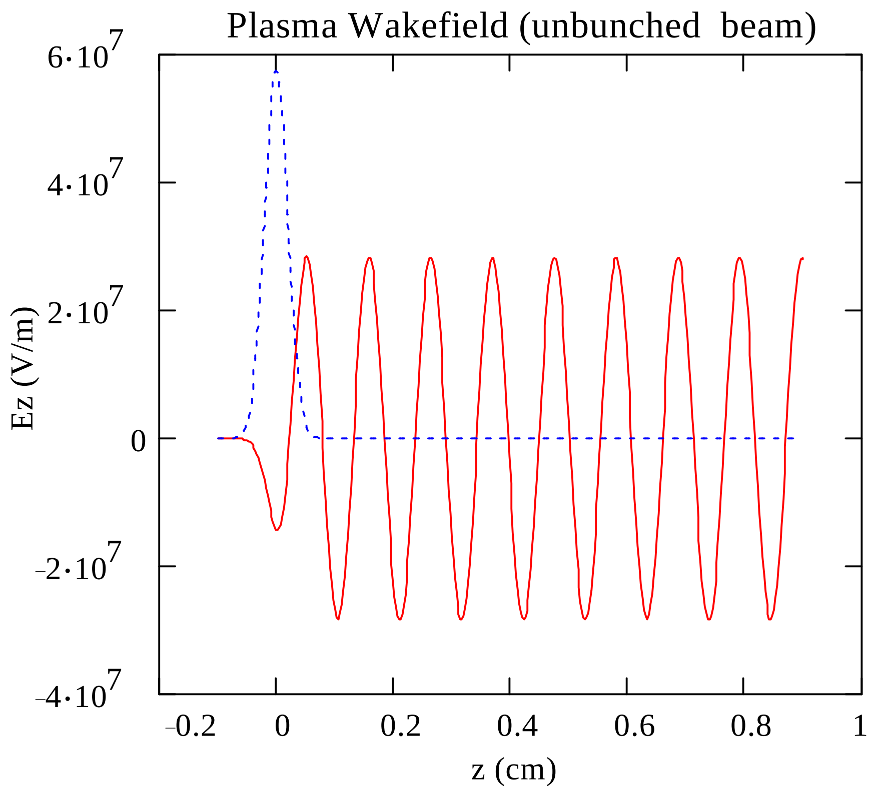

Figure 4. WF generated by the unbunched electron beam. The plasma density is adjusted lower to compensate the effects of long bunch length. The maximum WF produced here is only 20 -30 MV/m, in comparison with 5 GV/m of the bunched cases (Figure 2 and 3).

Conclusion:

We have studied a new plasma excitation scheme. Although most of arguments presented here are using the simple linear superposition, but it nevertheless proves the concept. The key word is "FEL bunching", therefore enhances the acceleration gradient by a factor of hundreds. Extend this work into the non-linear regime would be more interesting (it will be comparable with Michigan group's work). One short coming of this scheme could be that acceleration and maintenance the bunched beam after it has been generated in undulator.

Note: Direct all comments to wg@hep.anl.gov